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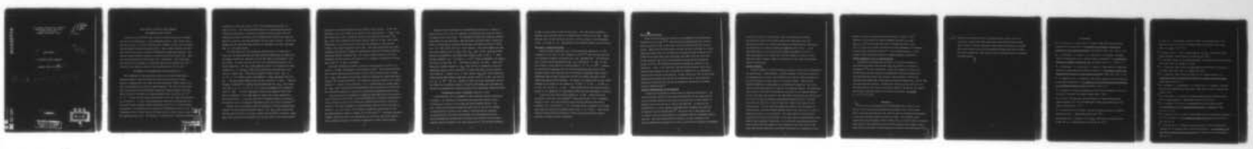

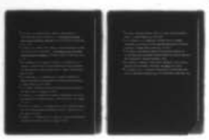

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FINAL REPORT

TO OFFICE OF NAVAL RESEARCH

CONTRACT N00014-75-C-~~786~~ 0786

(9) Rept. for Mar 75 - Feb 76.

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FINAL REPORT TO OFFICE OF NAVAL RESEARCH

FOR CONTRACT N00014-75-C-0786

Contract N00014-75-C-0786, which covered the period March 1975 to February 1976 was for the development of superconducting cavities. This contract was a successor contract to several contracts which included in their work statements the development of superconducting cavities. These earlier contracts included other work in the areas of cryogenic development and high energy physics. The two most recent previous contracts are N00014-67-A-0012-0076 (April 1973 - March 1975) and N00014-67-A-0112-0061 (April 1971 - March 1973). This final report will include a brief summary of superconducting cavity development from 1961 to 1971 and a more complete summary of this development from 1971 to 1976.

DEVELOPMENT OF SUPERCONDUCTING CAVITIES PRIOR TO 1971

The development of superconducting cavities at the High Energy Physics Laboratory (HEPL) at Stanford University began in 1961 in hopes of using cavities to upgrade the 1 GeV linear electron accelerator at HEPL, which was at that time supported by the Office of Naval Research. The 1 GeV electron accelerator achieved its acceleration using conventional copper microwave structures which limited the accelerator to pulsed operation with a duty factor of 10^{-3} to 10^{-4} because of their high microwave power loss at the large field required for acceleration. In 1961, it had already been shown that superconducting cavities could support microwave fields with quality factors of a few million which corresponded to an improvement over copper by an "improvement factor" of 100. The "improvement factor" is the ratio of the power loss in a copper cavity to that of the superconducting cavity. In principal, it appeared that it should be possible to achieve an improvement factor of 10^6 for superconducting cavities at about 2^o Kelvin. This large improvement factor for superconducting cavities offered the opportunity to construct a microwave structure which could continuously accelerate electrons, and thus substantially increase the range and quality of electron scattering experiments for the study of nuclei. It was also thought that the superconducting cavities may eventually have other continuous high rf field applications.

The investigation of superconducting cavities began at a modest level. There were two superconductors with high transition temperatures and high critical magnetic fields that appeared to be the most useful to investigate; lead and niobium. Of these, lead was the first to be investigated because of its easier preparation. The first superconducting cavity to be produced and tested at HEPL was a 2.8 GHz TE_{011} - mode cavity prepared by electroplating a lead layer on a copper base.[1] This cavity achieved a quality factor (Q_o) of 4×10^8 at 1.8^o Kelvin, which corresponded to a large improvement factor of $\underline{10^4}$. The peak surface magnetic field in this cavity was 70 Gauss. Improved cryogenic techniques[2] for cooling the superconducting lead TE_{011} - mode cavity later gave a Q_o of 5×10^9 at 1.8 K which corresponded to an improvement factor of $\underline{10^5}$. In these experiments a peak surface magnetic field of 270 Gauss was achieved; a level high enough to support the fields required for a linear accelerator. It was also found that the ambient magnetic field played an important role in limiting the improvement factor that could be achieved.[2,6]

Further work was required to show the feasibility of using superconducting cavities for accelerators and similar devices. The TE_{011} - mode cavities that had been tested differed in one major respect from accelerator structures; namely TE_{011} - mode cavities had essentially zero electric field on their surface while accelerator structures had large electric fields on their surface. To test the importance of electric fields on the surface of the lead cavities, a TM_{010} - mode lead cavity and a 3-cell accelerator structure were produced and tested.[3] The TM_{010} -mode cavity achieved a peak axial electric field of 10 MV/m with a power dissipation of 2.5 watts and the 3-cell structure achieved an axial field of 15 MV/m with a power dissipation of 100 wats. This work demonstrated that superconducting lead cavities designed for accelerators would have difficulty achieving improvement factors of greater than 10^4 without further advances in the lead technology and that electron field emission is an important consideration for peak axial fields of 10 MV/m and greater.

With this information available a prototype superconducting accelerator injector at 950 MHz was designed, constructed and tested.[9] The prototype included both a superconducting lead accelerator structure about one-half meter in length and a TM_{010} - mode superconducting lead cavity for measuring the longitudinal phase spread of the electron beam bunch. The accelerator structure operated at an energy gradient of 3 MeV/m and accelerated a 20 μA electron beam in a stable manner. The TM_{010} - mode cavity operated synchronously with the accelerator structure and was successfully employed to measure the electron beam longitudinal phase spread.

Concurrent with the development at superconducting lead cavities for accelerators, there was an effort both to study superconductors at microwave frequencies on a more fundamental level and to develop the promising superconductor niobium for cavities. The surface impedance of superconducting lead and tin were measured in detail at 2.8 and 12 GHz as a function of temperature and compared to both the phenomenological theory of Pippard and the BCS theory.[4-6] The Pippard phenomenological theory was found to be adequate,and the BCS theory agreed with measurements covering a range of ten thousand in magnitude to within several percent.

Niobium had been considered for superconducting cavities for a number of years at HEPL, and a number of techniques for depositing thin layers of niobium on copper cavities were probed. The techniques included electroplating, chemical vapor deposition and sputtering. HEPL and Varian Associates began a cooperative effort of investigating niobium by fabricating solid niobium cavities at X-band (8.2 - 12.4 GHz), which are about 3 cm in diameter. Very rapid progress was made with this technique, and in a short time TE_{011}-mode 12 GHz cavities of high quality were produced by ultra-high vacuum firing at about 2000^{o} C .[7] These cavities achieved Q_o's of as high as 4×10^{10} which corresponded to an improvement factor of more than 10^{6}, and fields as high as 440 Gauss . These techniques were rapidly extended to TM_{010}-mode cavities to demonstrate that large improvement factors could be achieved in cavities with large electric fields on their surfaces.[8] Finally, in an 8.6 GHz niobium TM_{010}-mode cavity fabricated using electron beam welding a peak axial electric field of 47 MV/m was achieved at a Q_o of 10^{10} (ref. 10). Because of these very large "improvement factors" and fields for the niobium cavities, the work on developing lead superconducting cavities was abandoned and a vigorous niobium cavity development program was begun.

SUPERCONDUCTING CAVITY DEVELOPMENT FROM 1971 to 1976

Superconducting cavity development at HEPL during this period concentrated on niobium. The techniques of fabricating and processing niobium cavities at X-band were extended to both larger and lower frequency cavities. The work under the ONR contract during this period was not directed at building a superconducting accelerator, but rather at investigating the properties of superconductors that limit the performance of superconducting cavities. These investigations included work on electron field emission, electron multipacting, thermal breakdown of the superconducting state, and detailed comparison of type II superconductors with the BCS theory. Also, the initial attempts at applying superconducting cavities to highly stable oscillators were made. Papers produced under the ONR contracts from 1971 to 1976 are given in the bibliography as ref. 11 through ref. 31. Approximately, four additional papers will be written.

Extension of Niobium Technology:

Niobium cavities composed of one to seven cells were produced at 1.3 GHz (diameter of 20 cm) and 2.8 GHz (diameter 10 cm).[12,20] These cavities were all of a cylindrical geometry operating in the TM_{01} waveguide mode. The investigation of these cavities demonstrated that Q_o's achieved at 1.3 and 2.8 GHz were similar to those achieved at X-band (range of 10^9 to 5×10^{10}) . However, it was found that phenomena such as electron multipacting and electron field emission played a more important role in limiting the achievable field at lower frequencies than at higher frequencies and that the maximum achievable fields scaled approximately with frequency. For example, the highest peak electric fields achieved on the surface of the niobium are 16 MV/m at 1.3 GHz , 35 MV/m at 2.8 GHz and 70 MV/m at 8.6 GHz . These results led to more detailed investigations of the properties of superconductors that limit the performance of cavities.

A number of very large niobium cavities at 1.3 GHz , which are used as accelerator structures, were produced.[28] These cavities are 20 cm in diameter and 565 cm long. The investigation of these cavities show that they achieve excellent Q_o's of typically 2×10^9 and fields which correspond to an average axial electric field for an electron beam of from 2 to 4 MV/m . These characteristics demonstrated the usefulness of large scale superconducting niobium cavities for linear electron accelerators.

Electron Field Emission:

Electron field emission was observed and investigated in superconducting niobium cavities at HEPL.[12,25] These observations demonstrated that electron field emission was large at much lower electric fields than may have been expected. Large electron-field-emission currents can not be tolerated in a superconducting cavity since the electrons are accelerated to high energy by the rf fields and can give large power dissipation upon impact with the cavity wall. It was found that the electron field emission currents could be reduced by factors of 10^4 to 10^6 by helium-ion sputter processing the cavities at low temperature. Also, it was found that improved vacuum techniques could reduce electron field emission as well as decrease the magnitude of Q_o degradation resulting from electron field emission. Further study of all the electron-field-emission data revealed that electron field emission was not only enhanced by geometrical projections but also by low-temperature surface-states probably caused by adsorbed atoms.[22]

Electron Multiplication and Multipacting:

Various cavity properties are the result of electron multiplication. Two cavity properties which have been observed extensively are the energy distribution of photons produced by the impact of electrons and rf field regions of enhanced power absorption due to electron multipacting. To study electron multiplication a computer program using Monte-Carlo techniques was developed to simulate electron multiplication.[26] The initial use of this program was to produce a photon spectrum which was in agreement with the experimental photon spectrum. This work demonstrated the importance of back scattering in the electron multiplication problem in as much as electrons with energies corresponding to as much as twice the full voltage across the cavities were produced. The simulation program went through considerable improvement after this initial use and has just recently been applied to determining the trajectories and conditions for electron multipacting in single-cell cavities. A very interesting result is that the electron multipacting which is of the one point type appears to be located near the outer diameter, and there is some indication that a suitable change in the geometry of the cavity may eliminate electron multipacting.

Thermal Breakdown:

Thermal breakdown in superconducting cavities was studied both experimentally and theoretically. Experimentally, thermal breakdown in cavities was observed by increasing the rf field to the breakdown level where the power absorption in the cavity increased a large amount in an unstable manner. Theoretically, thermal breakdown was investigated by calculating the temperature rise on the surface of the superconductor to which the rf fields are applied. The temperature rise was due to the heat flow through the cavity wall to the liquid helium bath in which the cavity was immersed. The theoretical calculations were made for both the case of an ideal homogeneous superconducting surface and for a non-ideal case which was modeled by a strip of high loss lying on the surface of the superconductor. For the ideal superconducting surfaces, the theoretical calculations gave a thermal breakdown magnetic field of 1500 Gauss at 1.4 K for an X-band cavity with a 2.5 mm thickness. The large magnetic breakdown field observed on an X-band cavity at HEPL is 1070 Gauss which is approaching the value given by the theoretical calculation. For a non-ideal superconducting surface with a lossy strip wide compared to the thickness of the cavity wall, it was found that thermal stability is essentially determined by the properties of the

Kapitza boundary resistance which becomes unstable at about 1 W/cm^2. Theoretical calculations of thermal breakdown were made for X-band Nb_{30}-Ta_{70} alloy cavities and were useful in determining that a lossy strip or region whose surface resistance was field independent is inadequate to explain the experimental results.[31] A more detailed paper is in preparation to give the general results of thermal breakdown calculations.

Surface Impedance of Type II Superconductors:

Experimental investigations were made of the surface impedance of superconducting niobium, tantalum and a Nb_{30}-Ta_{70} alloy as a function of temperature.[29,31] These experimental results were compared in detail with the BCS theory and much information regarding the electronic parameters of the superconducting surface were learned. These parameters included the superconducting energy gap, superconducting transition temperature, electron mean free path and fermi velocity. Of particular interest was the result that the BCS calculation of the surface resistance of niobium at X-band fit the experimental surface resistance within a few percent over almost six decades (2×10^{-8} to 10^{-2} ohms).

CONCLUSION

The work on superconducting cavity development under contract to the Office of Naval Research has provided those working in this field at HEPL with an exciting and productive time, and this work has contributed immeasurably to the superconducting accelerator project at HEPL. The pioneering superconducting cavity development effort at HEPL with its excellent results encouraged other groups in the United States and in other countries (West Germany, Japan, Great Britain and France) to begin programs in developing superconducting cavities.

next page

cont Although the principal interest in superconducting cavities was for use in particle accelerators, other applications have been seriously studied. These include rf particle separators, high stability oscillators, very high power pulsed radar sources, electro-mechanical energy conversion for micro-wave power transmission, high voltage electron microscopes, and rf confinement of fusion plasmas.

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